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Detection of plasma equilibrium shifts with fiber optic sensing of image currents

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The radial equilibrium position of Reverse Field Pinch experiments is determined by the $j \times B$ force on the plasma. The current density is that of the toroidal plasma current and the B field is the vertical magnetic field which is present in the plasma. This magnetic field is the result of several components. The main field, generated by the toroidal current windings, is corrected by adjustable trim windings to achieve a desired equilibrium position. There is an additional component to the field due to induced image currents in the close fitting conducting shell which encircles the plasma. These currents vary in time due to the finite L/R time of the conducting shell. It is the object of this paper to investigate the possibility of measuring these shell currents accurately using fiber optics so as to provide an analog signal to the equilibrium feedback circuit.

Assuming a steady plasma current, I_p, the magnitude of the induced shell image currents is related to the equilibrium plasma shift by the equation[1]

$$\frac{dI_{shell}}{d\theta} = \mu_0 \frac{\Delta}{\eta\pi} I_p \dot{\xi} \cos\theta \tag{1}$$

where Δ is the shell thickness, η the shell resistivity, $\dot{\xi}$ the time derivative of the plasma equilibrium shift from the origin, and θ the poloidal angle.

The anticipated fiber configuration to measure this current is illustrated in Fig. 1. Holes are drilled through the metallic shell and two fiber coils are wound through the shell. The measurement is a differential measurement as the sign of the current is opposite for the inside and the outside coils. The instrumentation to measure this current is the same as that used in Ref. 1. The only modification, shown in Fig. 2., is that the reference signal is derived from the light which has passed through one of two coils rather than from the light entering a single fiber.

Fiber optic Faraday rotation sensors offer several advantages over conventional Rogowski coils for such a measurement. If Rogowski coils were to be employed great care would be required to orient the coil turns. For times short compared to the L/R time of the shell there will be almost complete exclusion of the magnetic field from the shell. This means that there will be almost equal and opposite currents running on the inside and on the outside of the shell. The magnitude of each of these currents will approximate that of the toroidal plasma current. For the ZT-P experiment[3] these currents will be about 50 kA while the difference current which we are trying to measure is on the order of 100 amps. Rogowski coils, one inside and one outside the shell, would be subtracting two large numbers so that accurate orientation and uniform winding of the sensor coils would be extremely critical.

A fiber sensor for either the inside or outside coil is also differencing the surface currents but the nature of the fiber sensor avoids many construction problems. The actual positioning of the fiber is not important as the signal is proportional to the spatial integral of the current which passes through the fiber loop. Another attractive feature of a fiber optic measurement is the ability to have several windings which while looping through the shell, as shown in Fig. 1., are also constructed so that successive windings of the coils are located at different toroidal positions. In this way an average over some toroidal portion of the experiment is easily achieved.

While avoiding many of the problems associated with Rogowski coils, fiber current sensors are subject to their own set of problems. Bending of the fiber and pressure on the fiber will induce an unwanted linear birefringence which can destroy the measurement or, at least, cause errors.[4] Twisting of the fiber mitigates these effects. Three different twisted fibers have been produced by EOTec. All of their fibers use an extremely low intrinsic linear birefringence fiber which is then twisted to induce a circular birefringence bias. Their original fiber has an outside diameter of 125 μm and a twist rate of 15 turns/m. They have recently produced two other new fibers one of which has 125 μm OD. with 60 turns/m and a smaller, 80 μm OD. fiber with 100 turns/meter. We have tested all three fibers in an experimental environment by repeating the toroidal plasma current measurement on the ZT-40M experiment[2]. All gave about equivalent results requiring about a 5% change in the Verdet constant of the silica to keep the agreement between fiber sensor and Rogowski coil/Pearson transformer always within 1 %.

The linear birefringence introduced by bending has been calculated[5] as

$$\delta_b = 0.25kn^3(p_{11} - p_{12})(1 + \nu_p)\frac{\rho^2}{R^2} \tag{2}$$

where p_{11} and p_{12} are the components of the strain-optical tensor of the fiber material, ν_p is the Poisson's ratio, ρ is the radius of the fiber and R is the radius of the bend. The induced circular birefringence produced by twisting the fiber is given by the following formula [6]

$$T = -n^2(p_{11} - p_{12})\tau/2 \tag{3}$$

where τ is the twist. The important parameter to make an accurate measurement of the current[4] is $\delta/2T$:

$$\delta/2T = 0.25kn(1 + \nu_p)\frac{\rho^2}{\tau R^2} \tag{4}$$

This shows that the smaller diameter more highly twisted fiber should yield better measurements.

As mentioned before the intended installation to prove this measurement on is the ZT-P device at Los Alamos. This is a small reversed field pinch with a minor diameter of 20 cm. and an eighth inch stainless steel shell. In designing such an experiment one is not free to have arbitrarily large radii of curvature bends for the fiber. Other constraints of the machine dictate that the maximum radius would be 1.3 cm.

To test whether this would permit a reasonably good measurement the following model was taken for the fiber sensor. The fiber is assumed to be a racetrack form consisting of straight sections of fiber which have l_1 = 17 cm length and half circle ends which have a radius of 1.3 c.m., l_2 = 4.08cm. Assuming a uniform magnetic field at the fiber, the Jones matrix representation of one half a turn of this sensor is then the product of two matrices

$$\mathbf{M} = \begin{pmatrix} \cos((T+F)l_1) & -\sin((T+F)l_1) \\ \sin((T+F)l_1) & \cos((T+F)l_1) \end{pmatrix}$$

$$\begin{pmatrix} \cos(\phi/2) + i\sin(\phi/2)\cos\chi & -\sin(\phi/2)\sin\chi \\ \sin(\phi/2)\sin\chi) & \cos(\phi/2) - i\sin(\phi/2)\cos\chi \end{pmatrix} \tag{5}$$

where

$$\phi = \sqrt{\delta^2 + 4(F+T)^2}\ l_2$$

$$\tan\chi = 2(F+T)/\delta$$

with δ obtained from the bending formula and $2F$ is the Faraday rotation due to the magnetic field of the current. A full turn of the sensor is then $\mathbf{M}^2$ and the sensor is described as $\mathbf{M}^{2N}$ where N is the number of turns in the sensor . Numerical calculations were performed using calculated values for $\delta/2T$ for the various fibers.

In particular the results vary with the length of the straight section of the race track, and there are relatively sharply defined limits on $\delta/2T$, above which there is practically no sensitivity to current. (Even for large $\delta/2T$ values there are certain resonance lengths where there is good sensitivity, but since these result from an idealized model without regard to pressure birefringence or slight bend variations they do not constitute a practical option.)

Fig. 3. shows the calculate Faraday rotation ratios relative to the ideal case of no linear birefringence as a function of the straight section length for the 100 T/m fiber of 80 μm O.D. with 1.27 cm radius of curvature semicircles on a 50 turn coil. For certain discrete lengths there is a lack of sensitivity but over all the response is good. Fig. 4. shows the 60 T/m, 125 μm with the same end sections. Given that any real coil will have variations in winding it would seem unreasonable to expect to avoid trouble in this case.

To experimentally test this model, a fiber sensor was constructed using the 80 μm fiber. Forty-seven turns were placed on a coil form which approximated the theoretical model. The fibers were lightly constrained by foam rubber so that pressure birefringence[4] would be minimized. As a further precaution the curved end sections of the form were constructed in such a manner that they could be removed during operation so that there could only be bending birefringence in the end sections. Fig.5a. shows the best results that were obtained with this sensor. These results were for uniform windings and optimum orientation of the analyzer polarizer[4]. Fig. 5b. shows a typical result which was obtained when the fibers were distorted in their coil form to simulate nonuniformities in the radii of curvature which would be present in the winding of a practical sensor coil on an actual experiment. Under these conditions no orientation of the polarizer produced reasonable looking Lissajous figures. Above both current traces are the Lissajous figures associated with the current measurement. The smooth solid line is a least squares fit to a circle which is the form the Lissajous figure should take. The first peak of the current should be 12 kA. Note that even in the best case the amplitude is incorrect and the second peak of the current is smaller than the third showing there is considerable distortion in the measurement.

The results of these tests are not encouraging. The bend of the fiber seems to be too severe to make a practical measurement on ZT-P. The same fiber was next rewound on a similar form, but with the radius of the end sections 2.5 cm. The number of turns in this case was 39. As can be seen from Fig. 6a and 6b. this sensor is also not free from birefringence effects but a polarizer orientation was easily determined where accurate measurements of the current could be made. Next the current wire was passed through the center of the coil and returned through the sensor in a hole located 7 cm from the center of the fiber coil form. The net current through the sensor loop is zero in this case. The return wire is much closer to the end section where the bending exists and birefringence effects are maximized. With this configuration the cancellation was 1 part in 10^3. Fig 6c. shows the measured current. There is clearly an instrumental oscillation at about 40 kHz. If this can be eliminated the measurement will exhibit a cancellation in the 10^{-4} range. This would be adequate for a 10 % measurement if the shell surface currents differ by 100 A out of 100 kA. The data of Fig. 6. were taken with an optimum orientation of the analyzer polarizer. Fig. 7. shows the imperfect cancellation which is the result of choosing the worst orientation for the analyzer. With such a sensor having the larger bending radius a measurement could be practical.

The $125\mu m$, $60T/m$ fiber was also tested. 32 turns were placed on the smaller 1.3 cm radius form. Surprisingly, in contradiction to the calculations, the results of this test were almost as good as that of the previous fiber on the 2.5 cm form. In this case an optimum polarizer orientation was easily established. Good measurements of the current were possible and when the return current was passed back through the coil close to the curved end, the cancellation was 60 amps out of 12 kA. This result is almost but not quite good enough for a measurement on ZT-P. It does raise the hope that the model calculations are adequate and that something peculiar is occurring with the 80 μm fiber.

An obvious solution to the problems presented above is to deploy the fiber sensor on a larger experiment which would permit more gentle bending of the fiber. To this end a sensor was tested on a spare piece of the ZT-40M conducting shell. This shell is about 2 cm thick and made of cast aluminum. The minor diameter of the torus is 40 cm. Because the shell is split in the main plane of the torus, both the inner and outer sensors will be required to be split at this midplane also. The sensor coil sections will then either be put is series optically or electrically after installation. Ten turns of the 125 μm, 60 T/m fiber were wound on the shell and taped to it. Fig. 8. shows the inside of the shell with the fibers making a gentle turn so as to become almost parallel to the horizontal midplane slot so that while very little space is needed to exit from the inside of the shell the radius of curvature of the fiber is still greater than 5 cm at the tightest point. In this way the birefringence effects are rather small. The usual 12 kA test current was passed through the fiber loop at the point outside the shell where the bends were sharpest. With this arrangement excellent measurements of the current were obtained. The installation of fiber sensors on ZT-40M would require the removal and reinstallation of several shell sections which is a major operation. The future of this sensor experiment, using existing fibers, depends on when or if such work can be done.

An alternate approach to the fabrication of Faraday fiber sensors that is claimed to be much more tolerant to tighter bends is being developed by the York company in England.[7] It achieves a predominantly circular birefringence fiber by extreme twisting during the drawing operation of an intentionally high linear birefringence fiber. The large temperature dependence of the high birefringence is compensated by averaging over many wavelengths, each of different birefringence, with a broad band diode laser light source. Furthermore the light is reflected from the far end back through the fiber to the entrance end. The Faraday rotation doubles while the reciprocal distortions, such as linear birefringence, tend to cancel. The cancellation would be complete if Faraday rotation wouldn't change the polarization azimuth of the light encountering the distortions on the return path relative to the azimuth in the forward direction To maximize the cancellation the total Faraday rotation should be kept small. This puts a premium on very high sensitivity in order to retain reasonable dynamic range.

We propose to test this method with a phase conjugator replacing this reflector. Besides higher reflectivity, this might open the possibility of multimode fiber replacing the wavelength averaging achieved by the diode laser source and thereby also allow the much simpler input coupling of a multimode fiber.

Conclusions

The physical constraints on the ZT-P experiment are such as to make the desired measurements marginal with the present fiber available from EOTec. Something is wrong with the 80 μm fiber; possibly it does not really have the twist birefringence that was expected. On a physically larger device which allows large bending radii a shell current measurement would seem possible. The novel design of the York twisted hi-birefringent fiber offers hope that such a measurement is practical on the smaller ZT-P experiment.

References

1. V. S. Mukhovatov and V. D. Shafronov, Nucl. Fusion **11**, 605 (1971)

2. George I. Chandler, P. R. Forman, F. C. Jahoda, and K. A. Klare, "Fiber-optic heterodyne phase-shift measurements of plasma current", Appl. Opt. **25**, 1770 (1986)

3. K. Schoenberg et al, ZT-P: An advanced air core reversed field pinch prototype, LA-10593-MS

4. P. R. Forman and F. C. Jahoda, "Linear birefringence effects on fiber-optic current sensors", accepted for publication in Appl. Opt.

5. S. C. Rashleigh, "Origins and control of polarization effects in single-mode fibers", J. of Lightwaves Technology, **LT-1**, 312 (1983)

6. R. Ulrich and A. Simon, "Polarization optics of twisted single-moded fibers", Appl. Opt. **18**, 2241 (1979)

7. Private comunications and R. I. Laming, D. N. Payne, and L. Li, "Current monitor using elliptical birefringent fiber and active temperature compensation" SPIE Vol 798, Fiber optics sensors II, 283 (1987)

Figure Captions

1. Schematic drawing showing the inner and outer fiber coils on the shell of a toroidal experiment. For clarity only two turns per coil are shown.

2. Schematic drawing of optics used for the heterodyne measurements of the laser light. The combination of a 40 MHz Bragg cell, the wave plates, and prism produces linearly polarized light whose direction of polarization rotates at 20 MHz.

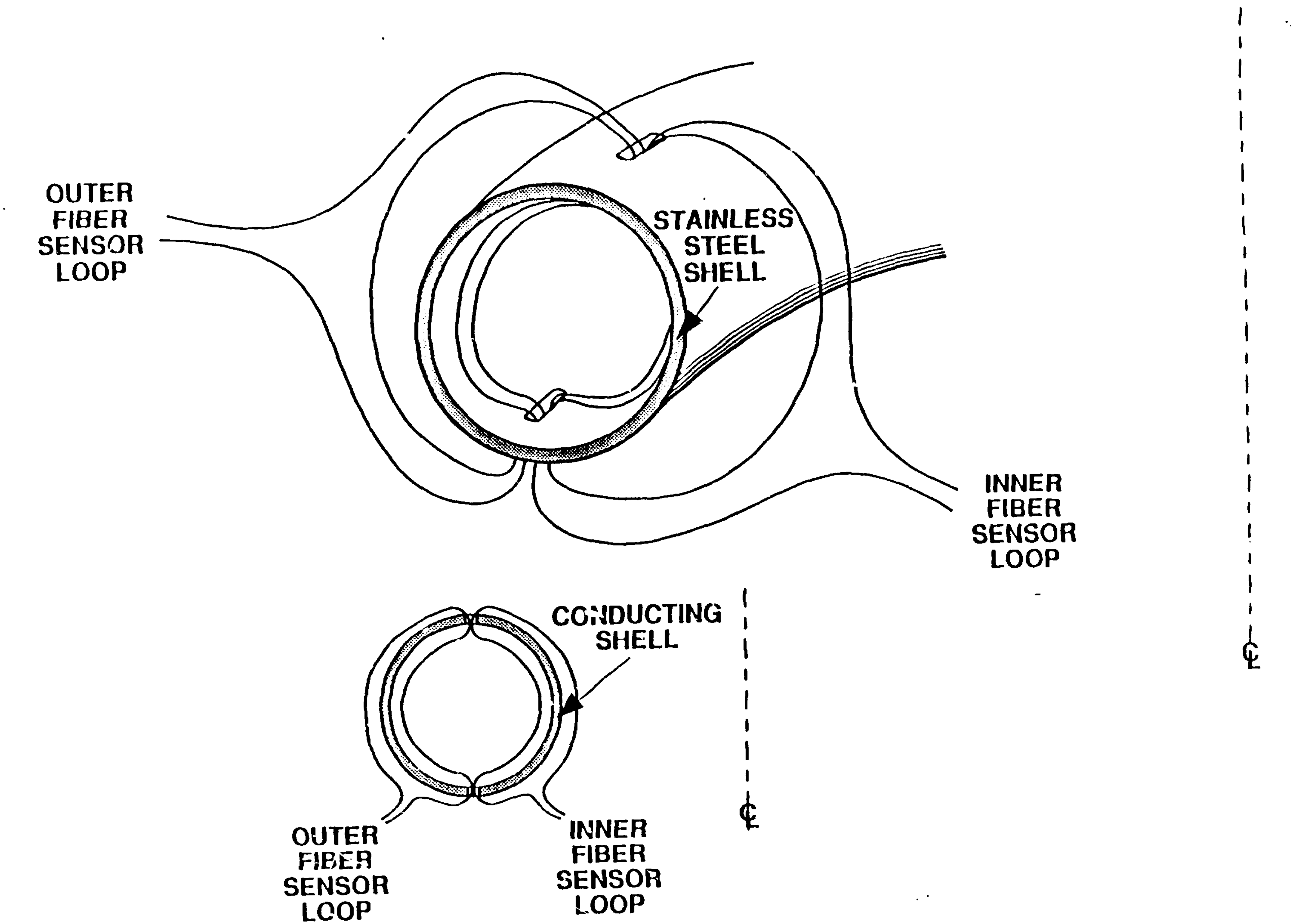
3. Calculated dependence of the 80 μm, 100 T/m fiber on straight section length, for 1.3 cm radius end sections.

4. Calculated dependence of the 125 μm, 60 T/m fiber on straight section length, for 1.3 cm radius end sections.

5. Current as measured with the $80\mu m$, $100T/m$ fiber. Shot 526 is with optimum polarizer orientation and uniform windings. Shot 527 is typical of measurements with nonuniform windings. Above each trace is the corresponding Lissajous figure.

6. Current trace when the $80\mu m$ fiber was wound on a 2.5 cm radius coil form. Below the current trace is the residual when the current wire was returned through the fiber loop close to the curved ends, showing good cancellation.

7. Residual current trace similar to the previous figure but with the orientation of the analyzer polarizer chosen to produce the least cancellation. About 60 amps are registered when 12 kA are flowing.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STAINLESS STEEL SHELL
INNER FIBER SENSOR LOOP
℄
CONDUCTING SHELL
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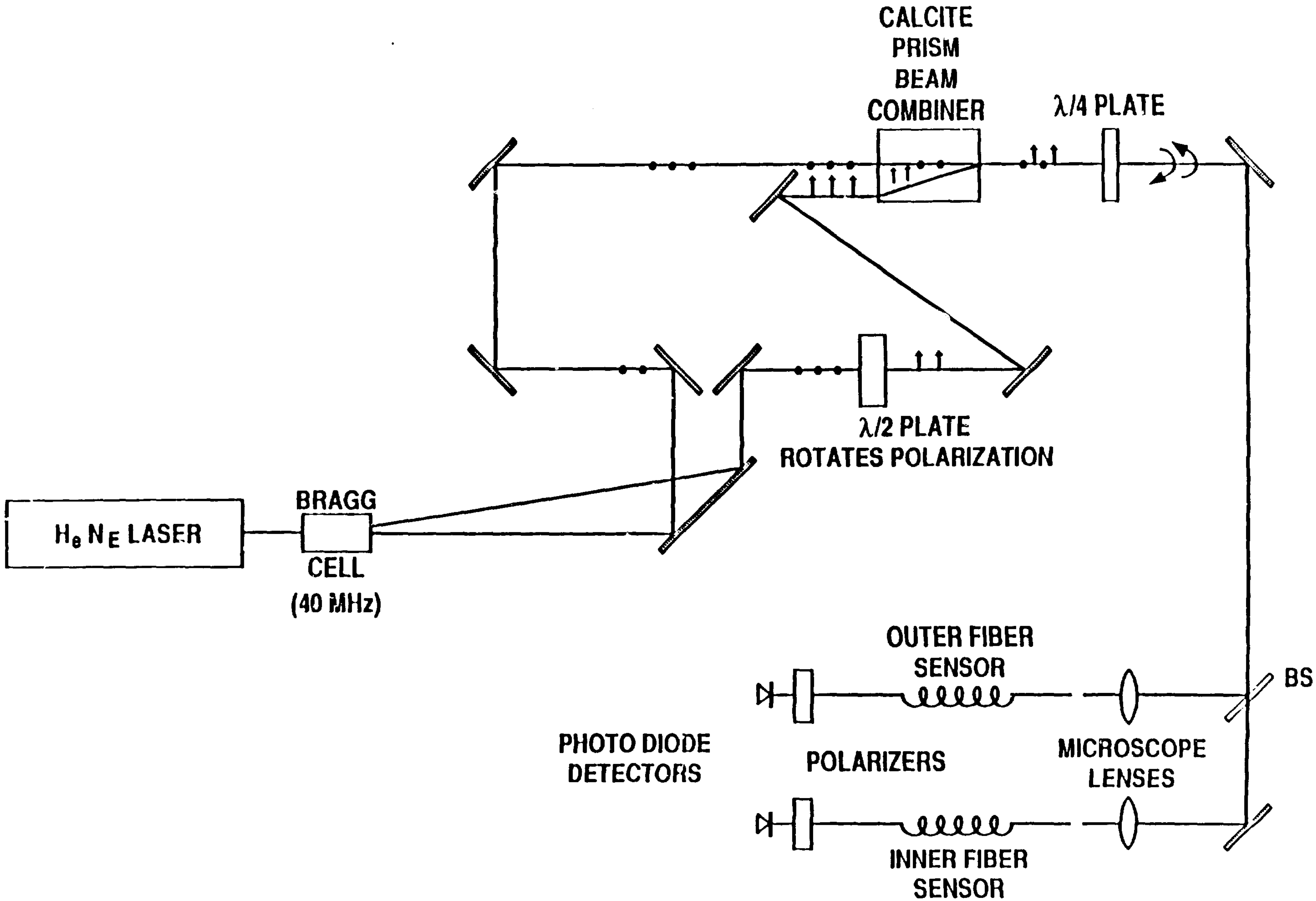
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PRISM
BEAM
COMBINER
λ/4 PLATE
λ/2 PLATE
ROTATES POLARIZATION
$H_e N_E$ LASER
BRAGG
CELL
(40 MHz)
OUTER FIBER
SENSOR
BS
PHOTO DIODE
DETECTORS
POLARIZERS
MICROSCOPE
LENSES
INNER FIBER
SENSOR

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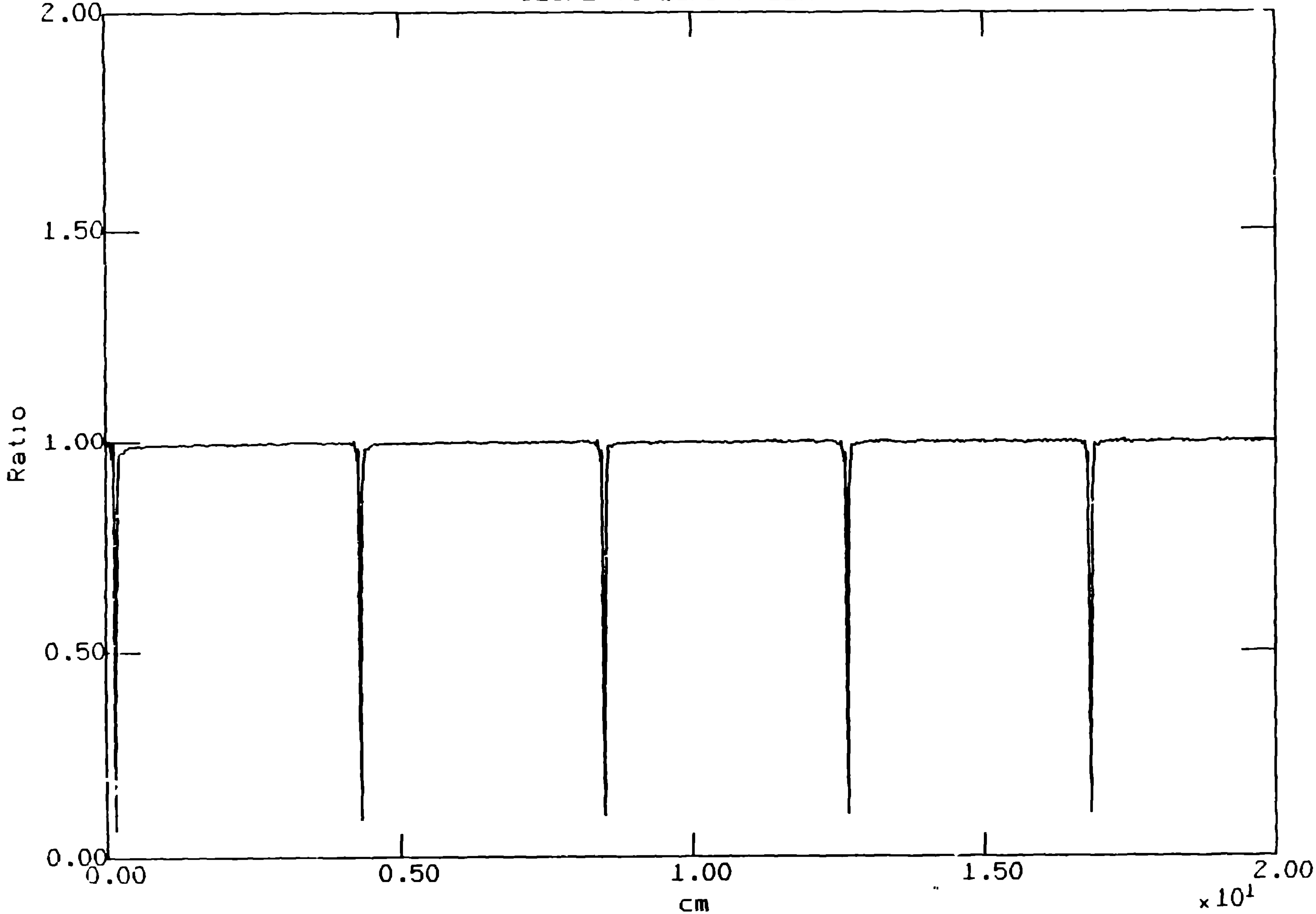
SLOPE VS LINEAR LENGTH



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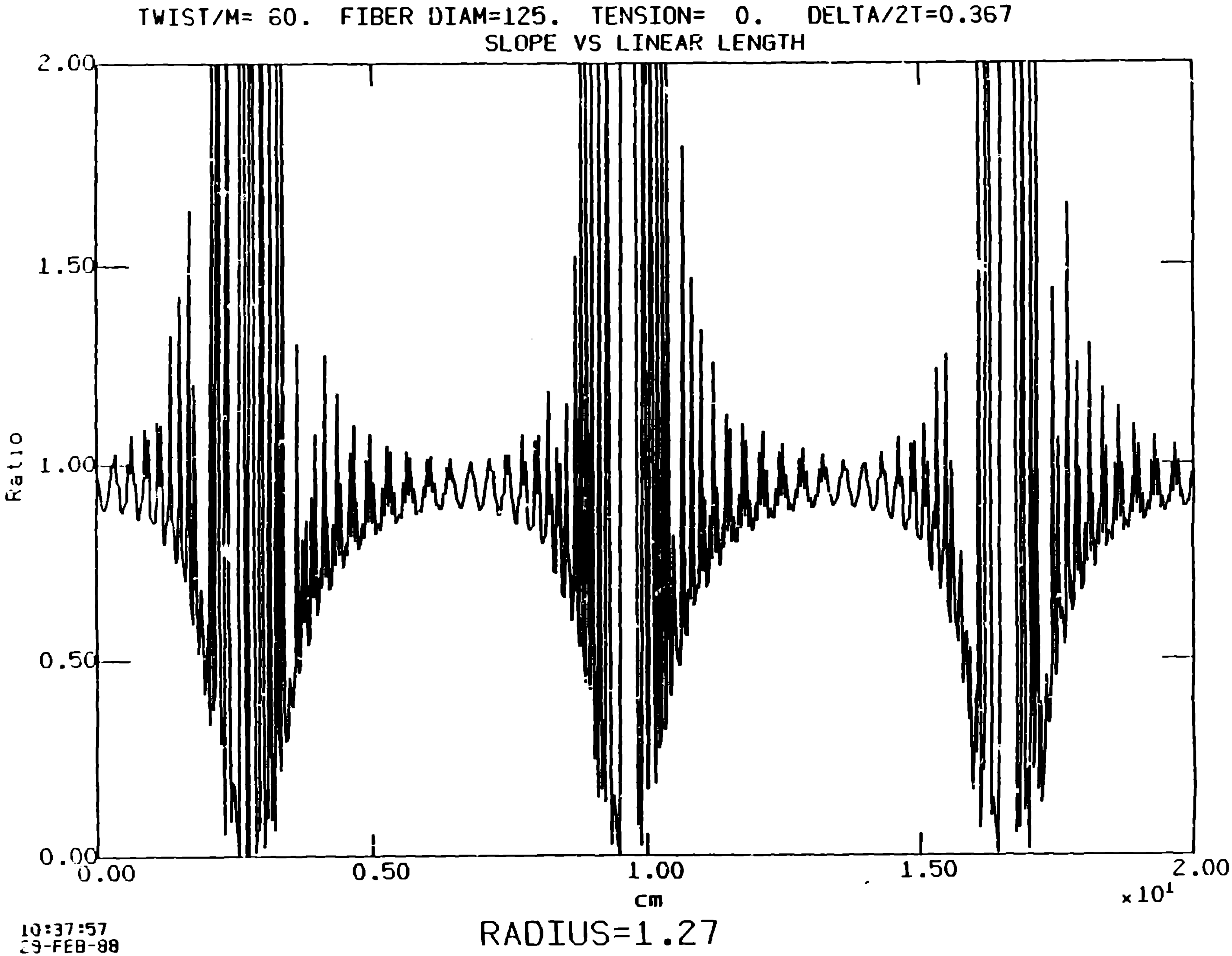
29-FEB-88



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SLOPE VS LINEAR LENGTH
Ratio
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
cm
x10^1
RADIUS=1.27
10:37:57
29-FEB-88

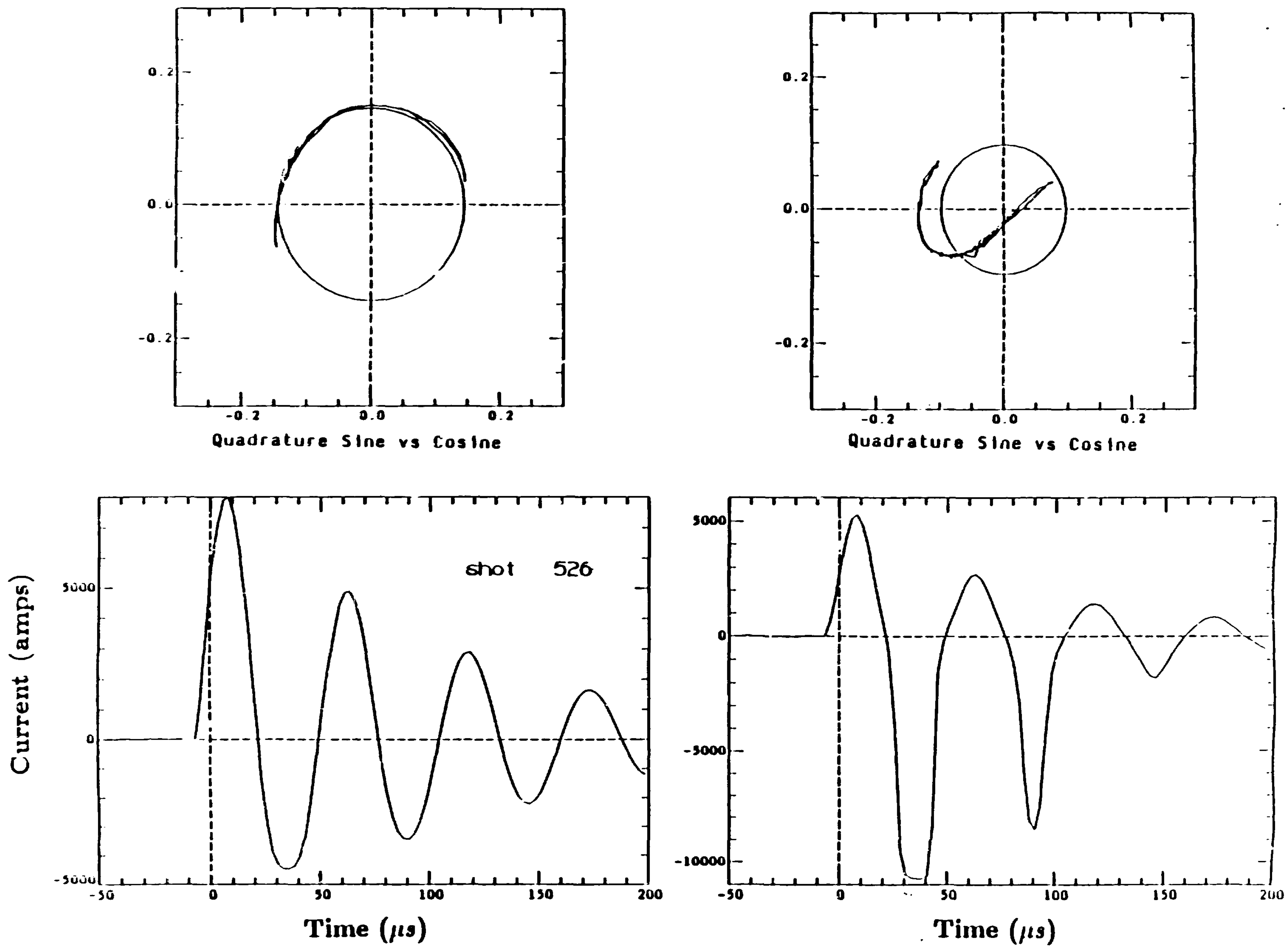
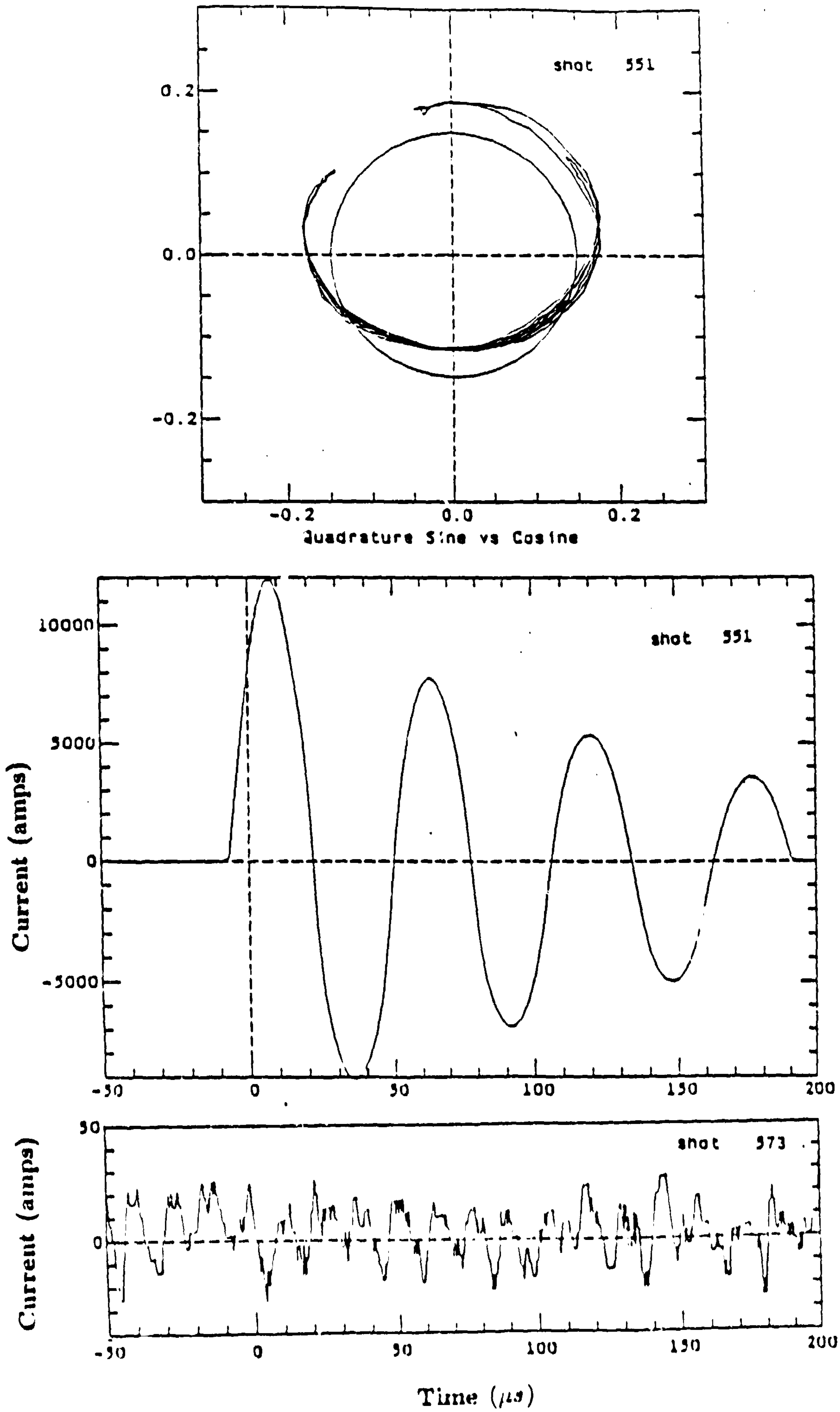
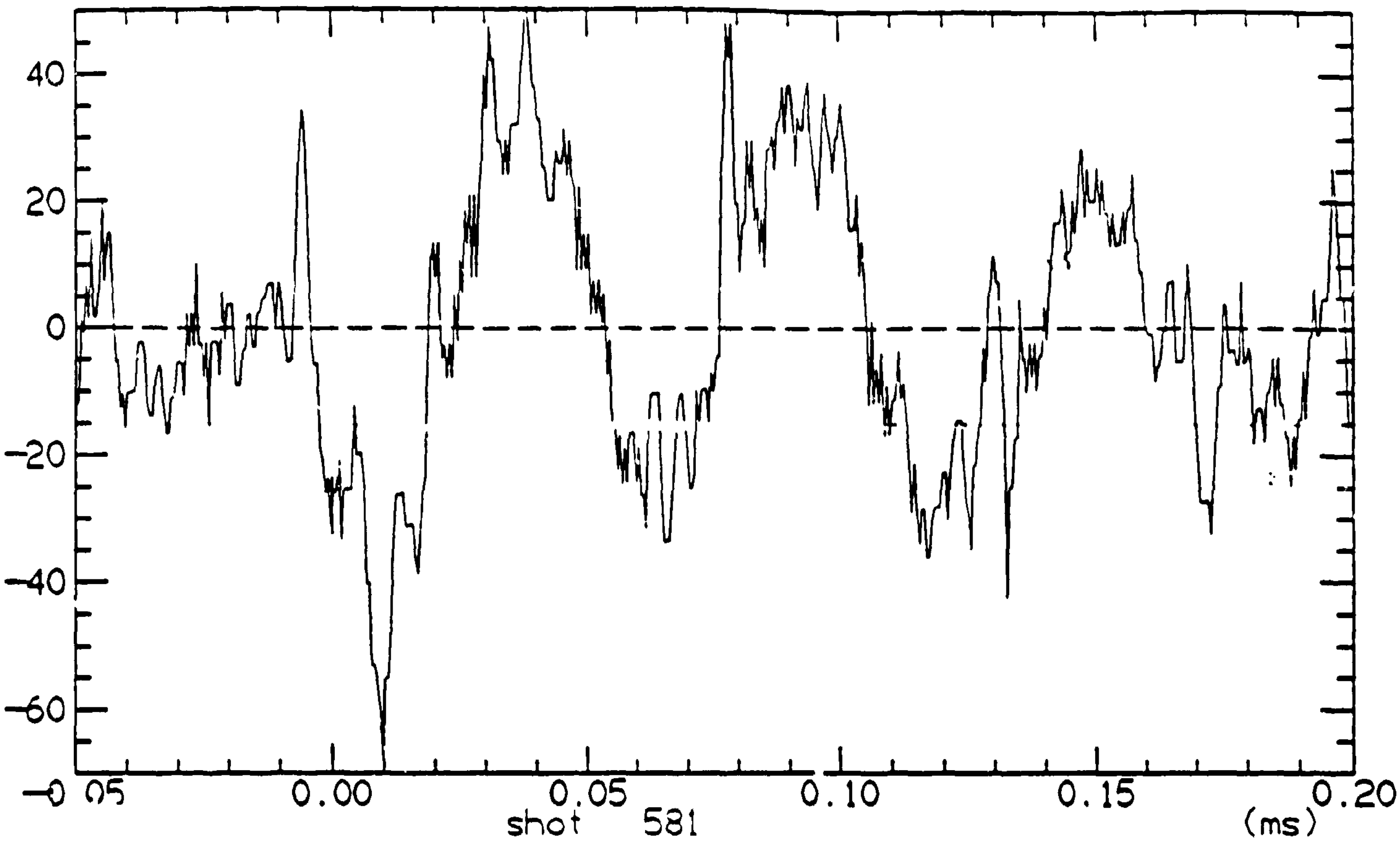

0.2
0.0
-0.2
-0.2
0.0
0.2
Quadrature Sine vs Cosine
0.2
0.0
-0.2
-0.2
0.0
0.2
Quadrature Sine vs Cosine
shot 526
Current (amps)
5000
0
-5000
-50
0
50
100
150
200
Time (μs)
5000
0
-5000
-10000
-50
0
50
100
150
200
Time (μs)

Fig 6



shot 551
0.2
0.0
-0.2
-0.2
0.0
0.2
Quadrature Sine vs Cosine
shot 551
10000
5000
0
-5000
Current (amps)
-50
0
50
100
150
200
shot 573
50
0
Current (amps)
-50
0
50
100
150
200
Time (μs)


40
20
0
-20
-40
-60
-0.05
0.00
0.05
0.10
0.15
0.20
shot 581
(ms)